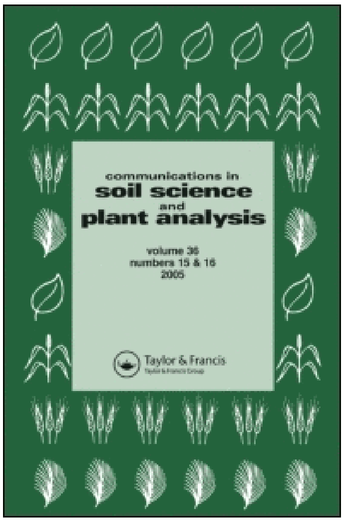

Communications in Soil Science and Plant Analysis
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597241

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To cite this Article Elrashidi, M. A. , Persaud, N. and Baligar, V. C.(1998) 'Effect of fluoride and phosphate on yield and mineral composition of barley grown on three soils', Communications in Soil Science and Plant Analysis, 29: 3, 269 — 283
To link to this Article: DOI: 10.1080/00103629809369945
URL: http://dx.doi.org/10.1080/00103629809369945

COMMUN. SOIL SCI. PLANT ANAL., 29(3&4), 269–283 (1998)

Effect of Fluoride and Phosphate on Yield and Mineral Composition of Barley Grown on Three Soils

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ABSTRACT

In a greenhouse experiment, the effect of fluoride (F) and phosphorus (P) addition on the growth and mineral composition of barley (*Hordeum vulgare* L.) was studied in three different soils, Cahaba sandy loam (acid), Weld loam (neutral), and Haverson silty loam (alkaline calcareous). Four levels of F [0, 100, 400, and 1,000 mg kg^{-1} soil as hydrogen fluoride (HF)] and three levels of P [50, 150, and 550 mg kg^{-1} soil as phosphoric acid (H_3PO_4)] were used. The effect of P addition on the native soil F and the capacity of soil to sorb added F was investigated. Addition of P released some of the native F from the soil samples that did not receive any F. The amount of F released ranged from 0.135 to 1.860 mg kg^{-1} soil. The amount of F released from the soils decreased with increasing P addition. Most of F added was sorbed by the soil solid phase. The amount of F sorbed ranged between 74.0% and 96.3% of the added F. For both the acid and neutral soils, increasing P addition increased

F sorption at all F levels. In the case of alkaline soil, however, this effect was only clear at the low F level. The formation of insoluble F minerals may be enhanced by the addition of P to the soils. In the greenhouse experiment, F addition had a negative effect on dry matter yield (DMY) of barley grown on the acid and neutral soil while no effect was observed for the alkaline soil. These results may reflect the effect of F addition on the solubility of aluminum (Al) and other metals in the soils. On the other hand, increasing F addition from 50 to 550 mg kg^{-1} soil had no clear effect on DMY of plants in the three soils. The study also included the effect of F and P addition on their uptake by plants. Generally, addition of P depressed F uptake by plants grown on the three soils. On the other hand, increasing F addition depressed P uptake for the acid soil while no clear trend was observed for the neutral and alkaline soil. A significant positive effect of F addition on Al uptake was observed for both the acid and neutral soils. A highly significant correlation of 0.87 and 0.60 was obtained between soil extractable F and Al uptake for the acid and neutral soil, respectively. Addition of F to the alkaline soil resulted in minor increases in Al uptake. The effect of P addition, at different levels of F, on Al uptake was investigated for the three soils. For the acid soil, significant decrease in Al uptake was observed only at the highest F level. The effect of P addition on Al uptake was not clear in the other two soils.

INTRODUCTION

Relative to the enormous hazard of F contamination in the environment, little is known about the effect of F on the mobility of chemical species in the contaminated soils. The work of Polomski et al. (1982) was one of the few studies done on this area of research. In their study, various F solutions were leached through soil columns at a constant flow rate of 4 mL hr^{-1}. They concluded that F induced mobilization of Al, iron (Fe), and organic matter (OM) in the soils investigated. However at the flow rate used in the work of Polomski et al. (1982), the dissolved chemical species may not be in equilibrium with the soil phase especially in calcareous soils (Fluhler et al., 1982). Huang and Jackson (1965) studied the mechanism of reaction of F in solution with layer silicates and oxides of soils. They indicated that F forms Al and Fe complexes which disrupt the mineral surfaces. Similar studies on soils and soil minerals have been conducted by Semmens and Meggy (1966), Perrott et al. (1976), and Omueti and Jones (1977).

The ability of F ions to extract P from soils was first postulated by Dickman and Bray (1941). This led to the development of the Bray tests which employ acid fluoride reagents for extracting available P from soils (Bray and Kurtz, 1945). Later, Chang and Jackson (1957) used the differences in the extent of Al and Fe fluoride complex formation to develop the P fractionation technique for soils.

The interaction between F and P applied to soils was investigated in few studies. Prince et al. (1949) reported that addition of F at 360 mg L^{-1} as sodium fluoride (NaF) was injurious to buckwheat. They also noted that the toxicity, as reflected in yield, was reduced by increasing the rate of P application. Singh et al. (1979a) studied the effect of five levels of F (as NaF) and four levels of P [as potassium dihydrogen phosphate (KH_2PO_4)] on the yield and chemical composition of rice grown on two sodic soils of very high pH values. They concluded that increasing F above 50 mg L^{-1} decreased the yield of rice. The adverse effect of added F was eliminated by greater application of P. In another study, Singh et al. (1979b) concluded that application of both F and P resulted in higher extractability of each other in soils. They also reported that while there was a positive effect of P on soil extractable F, it had a negative effect on its uptake by wheat. The experimental findings of the above studies suggest that addition of P decreases or eliminates F toxicity in plants. However, these studies were conducted either in acid soils (Prince et al., 1949) or sodic soils of very high pH (Singh et al., 1979a, 1979b). No studies have been reported on naturally occurring neutral or calcareous soil. There is a need to study and compare these interactions simultaneously in various soils of wide range of properties.

The objectives of this study were i) to investigate how the interaction between added F and P affect the yield and chemical composition of barley grown in three soils differ greatly in their properties and ii) to determine the effect of added P on the release and sorption of F in these soils.

MATERIALS AND METHODS

Three soil samples of Cahaba (fine-loamy siliceous, thermic Typic Hapludults), Weld (fine, montmorillonitic, mesic Aridic Paleustolls) and Haverson [fine-loamy, mixed (calcareous) mesic Ustic Tortifluvents] series were selected for this experiment. The characteristics of these samples are as follows: Cahaba sandy loam (pH=4.75 and OM%=0.86), Weld loam (pH=6.57 and OM%=0.74), and Haverson silty loam [pH=7.50, and OM%=1.27, and calcium carbonate ($CaCO_3$) %=6.4]. Both Cahaba and Weld soils have no carbonates. More properties of these soils were given in previous reports (Elrashidi and Lindsay, 1986b, 1987).

In a previous study, Elrashidi and Lindsay (1987) concluded that additions of high concentration of F increased significantly the solubility of Al and manganese (Mn) for both the acid and neutral soils. Meanwhile, minor effects were observed for the alkaline soil. Therefore in this experiment, F treatments included four levels of F (0, 100, 400, and 1,000 mg kg^{-1} of soil) for the alkaline soil. For both the acid and neutral soils, the highest level of F was not used. Fluoride was added to soils as diluted hydrofluoric acid (HF) solution (100 mg F L^{-1}). The use of dilute HF simulated more nearly the conditions in the field where crops are subject to fumes from industrial plants. Ten separate increments were used to supply the amount of F required for each treatment. The study also included three levels of

P (50, 150, and 550 mg kg^{-1} of soil) added as diluted H_3PO_4 solution (10 mg P L^{-1}). All treatments were replicated four times. In total 144 plastic pots were used, each of 2-liter capacity.

One kg of air-dried soil (ground to pass through a 2-mm sieve) was added to each pot. A basal fertilizer application of 50 mg nitrogen (N) as ammonium nitrate (NH_4NO_3), 50 mg P and 63 mg potassium (K) as KH_2PO_4, 40 mg calcium (Ca) as calcium chloride ($CaCl_2 \cdot 2H_2O$), 20 mg magnesium (Mg) as magnesium chloride ($MgCl_2 \cdot 6H_2O$), 20 mg Fe as ferrous sulfate ($FeSO_4 \cdot 7H_2O$), and 5 mg zinc (Zn) as zinc sulfate ($ZnSO_4 \cdot 7H_2O$) was used for each pot. The solutions containing the amount of H_3PO_4 required along with the basal fertilizer applications were mixed thoroughly with the soil. Fifteen barley (*Hordeum vulgare* L) seeds were sown in each pot. After seven days the plants were thinned to 10 plants pot^{-1}. During the experiment, soil moisture was kept at field capacity by daily addition of the required amount of distilled water. When the plants were 20 days old, additions of dilute HF were made in irrigation water at 2-day intervals.

Thirty days after sowing, 25 mg of N as NH_4NO_3 was added in irrigation water to each pot. The tops were harvested when the plants were 60-day-old. The tops were rinsed with dilute hydrochloric acid (HCl) followed by several rinses with distilled water. The plant samples were dried at 60°C for 48 hours, weighed, and ground for analysis. Total F in plants was determined by a sodium hydroxide (NaOH) fusion selective ion electrode technique described by McQuaker and Gurney (1977). Phosphorus, Al, and Mn in plants were determined after digestion with a nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4) acid mixture (Jackson, 1967). Inductively coupled plasma optical emission spectrometry (ICP-OES) was used to measure the concentration of elements in the plant digest (Soltanpour et al., 1982).

After harvesting, the soil in each pot was air-dried, mixed thoroughly, and crushed to pass through a 2-mm sieve. Precautions were taken to separate plant roots from soil. The soil was extracted by shaking 20 grams of soil and 60 mL $CaCl_2$ solution in a 125-mL plastic bottle for 24 hours. The suspensions were centrifuged and filtered through Whatman 42 filter paper into plastic bottles. Fluoride was measured in the filtrate with a combination F electrode (Orion Instruction Manual, 1982). Phosphorus was determined by the chloromolybdic boric acid method after Peterson and Corey (1966). The pH of the solution was measured with a combination pH electrode.

The experimental data were subject to analysis of variance (ANOVA) to study the effect of soil, F and P addition, and their interactions on various dependent variables. Duncan's Multiple Range Test and regression analysis were used to examine means within soils.

The effect of P addition on native and added F was investigated for the three soils. The amount of native F released as mg kg^{-1} soil was calculated as follows:

$$\text{amount of F released} = F_{ex} + F_{ab}$$

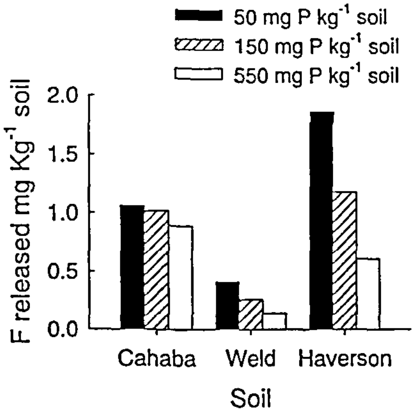

FIGURE 1. Effect of P addition (50, 150, and 550 mg P kg^{-1} soil) on the amount of native F released (mg F kg^{-1} soil) from the three soils.

where: F_{ex} is the amount of F (mg kg^{-1} soil) extracted with 0.01M $CaCl_2$ solution from the soil sample which received no F addition. The F_{ab} is the amount of F (mg kg^{-1} soil) absorbed by plant from the soil. For each F treatment, the amount of F sorbed by the soil was calculated as a percentage of added F as follows:

$$\text{F sorbed \%} = \{[F_{ad} - (F_{ex} + F_{ab})]/(F_{ad})\} \times 100$$

where: F_{ad} is the amount of F (mg kg^{-1} soil) added. The effect of P addition on the amount of native F released and the percentage of F sorbed by soils are shown in Figures 1 and 2, respectively.

RESULTS AND DISCUSSION

Significant effects of soil, and the F and P additions were found for most of the dependent variables investigated, namely dry matter yield, soil pH, total available F and P in soil, and F, P, Al, and Mn uptake by the plants (Table 1). Significant effects were also obtained for the interactions: soil x F, soil x P, F x P, and soil x F x P. Therefore, responses to F and P addition were measured by Duncan's Multiple Range Test and regression analysis within each of the three soils investigated (Tables 2, 3, and 4).

Soil pH

Addition of F decreased the pH of the three soils (Table 2). The magnitude of pH decreases followed this order: neutral soil > acid soil > alkaline soil. When

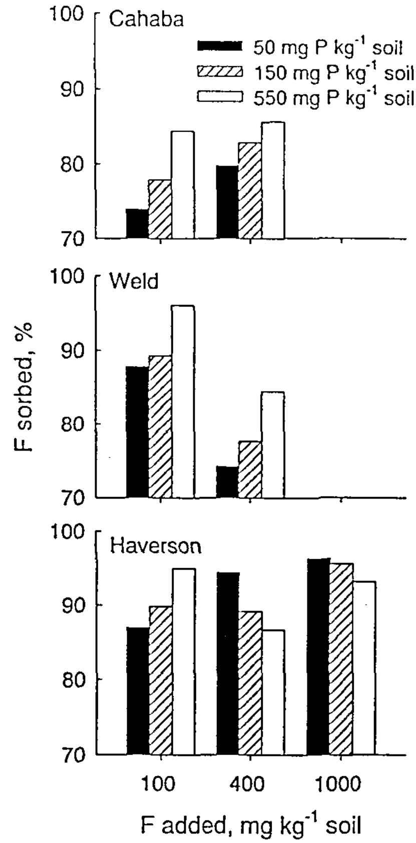

FIGURE 2. Effect of P addition at different levels of added F (100, 400, and 1,000 mg F kg^{-1} soil) on the percentage of F sorbed by the three soils.

HF was added to soil, HF and F ions acted oppositely on pH. The pH decreased with increasing hydrogen (H^+) ion concentration while F^- ions addition increased pH. The substitution of F^- for hydroxyl (OH^-) ions in various hydroxyl minerals such as clays and amorphous hydroxides has been suggested by many investigators (Huang and Jackson, 1965; Perrott et al., 1976).

Highly acid soils normally contain high amounts of Al and Fe hydroxides (Jackson, 1969). When F is added to these soils, OH^- ions are released in relatively higher concentrations than from soils containing less amounts of these hydroxyl minerals. Accordingly, HF addition is expected to be less effective in decreasing the pH of these acid soils. On the other hand, alkaline calcareous soils have high

TABLE 1. Analysis of variance for soil, fluoride, and phosphate addition effects on various dependent variables.

		Mean squares			
Source	DF†	Dry matter	Soil pH	F total	P total
		---g pot^{-1}---		--extractable mg kg^{-1} soil--	
Soil	2	147.6***	76.4***	2281.2***	10892.5***
Fluoride (F)	2	18.7***	1.07***	39780.0***	58.87***
Phosphate (P)	2	0.61	2.17***	421.0***	15702.4***
Soil x F	4	5.65***	0.42***	2121.0***	238.0***
Soil x P	4	2.14**	0.15***	454.8***	5767.8***
F x P	4	1.02	0.08***	97.47***	102.0***
Soil x F x P	8	0.73	0.07***	454.7***	242.3***
ERROR	81	0.47	0.01	10.45	3.27
		F	P	Al	Mn
		----------Plant uptake mg pot^{-1}----------			
Soil	2	432.0***	1519.2***	516.7***	927.7***
Fluoride (F)	2	174.9***	90.67***	913.7***	144.6***
Phosphate (P)	2	1.36	1473.0***	9.96	210.9***
Soil x F	4	91.35***	100.9***	425.1***	157.6***
Soil x P	4	12.22***	48.04*	78.37***	184.7***
F x P	4	7.06***	60.50***	35.28**	13.5
Soil x F x P	8	9.26***	33.85	96.99***	15.09***
ERROR	81	1.41	6.17	7.66	1.95

*, **, ***Indicate significance at 0.05, 0.01, and 0.001 level of probabililty, respectively.

†DF=degree of freedom.

TABLE 2. Effect of fluoride and phosphate addition on dry matter yield of barley, soil pH, extractable fluoride, and phosphate in the three soils.*

F applied mg kg^{-1} soil	Cahaba soil (acid)			Weld soil (neutral)			Haverson soil (alkaline)		
	P applied mg kg^{-1} soil								
	50	150	550	50	150	550	50	150	550
	Dry matter g pot^{-1}								
0	3.53cx	4.13cx	3.70bx	3.33ax	4.38bx	4.68bx	6.70ax	6.50ax	6.90ax
100	2.00bx	3.03by	3.38by	4.38bx	3.73abxy	4.90by	7.28ax	6.03ax	6.00ax
400	1.00axy	1.10ay	0.75ax	3.30ax	2.93ax	3.23ax	6.95ax	5.75ax	6.35ax
1000	-	-	-	-	-	-	6.38ax	6.60ax	6.40ax
	Soil pH								
0	4.75bz	4.41ay	4.25bx	6.55cz	5.91cy	5.39cx	7.49ay	7.45cy	7.25cx
100	4.64abz	4.41ay	4.21bx	5.83bz	5.56by	5.16bx	7.45ay	7.45cy	7.17cx
400	4.53ay	4.51ay	4.13ax	5.33az	5.23ay	5.00ax	7.34ay	7.29by	6.97bx
1000	-	-	-	-	-	-	7.24az	7.11ay	6.78ax
	Soil extractable F mg kg^{-1} soil								
0	1.01ay	0.95ay	0.83ax	0.38az	0.23ay	0.11ax	1.75az	1.10ay	0.55ax
100	25.88by	21.93by	15.50bx	11.93by	10.56by	3.85ax	12.80aby	9.99by	4.91ax
400	79.00cz	67.50cy	57.13cx	100.38cz	88.13cy	61.13bx	22.00bx	43.18cy	52.98bz
1000	-	-	-	-	-	-	36.53cx	43.95cy	67.75cz
	Soil extractable P mg kg^{-1} soil								
0	0.20ax	3.40by	23.35cz	5.00ax	15.18ay	95.73bz	1.55ax	6.95ay	8.43az
100	0.15ax	2.13ay	15.85bz	5.79ax	17.73ay	105.00cz	1.50ax	8.60by	16.50bz
400	0.10ax	3.66by	11.39az	7.28bx	18.08ay	71.70az	1.29ax	9.65bcy	27.20cz
1000	-	-	-	-	-	-	1.28ax	10.58cy	35.95dz

*In each soil, means within columns with the same letter (a,b,c, or d) and means within rows with the same letter (x,y, or z) are not significantly different at the 5% level according to Duncan's Multiple Range Test.

content of carbonates which can neutralize the added H^+ ions. This may explain why the magnitude of pH decreases was relatively higher for the neutral soil than for both the acid and alkaline soils.

Expectedly, the addition of P decreased the pH for the three soils (Table 2). It appears that H_3PO_4 addition along with HF has an accumulative effect on H^+ concentration in these soils. This suggests the absence of any interaction between P and F in soils that may enhance or inhibit each one effect on the pH.

Fluoride Release and Sorption by Soils

Phosphorus addition released a part of the native F from the three soils (Figure 1). The amount of F released ranged from 0.135 to 1.860 mg kg^{-1}·soil. The magnitude of F released from the soils followed this trend: alkaline soil > acid soil > neutral soil. This trend could be explained by the effect of P addition on the pH of the three soils. The data in Figure 1 also show that the amount of F released is decreasing with the increase in P addition. This effect could be explained by reactions between P and F and the formation of insoluble F minerals.

The results given in Table 2 show that most of F added to the soils was sorbed by the solid phase. The amount of F sorbed ranged between 74.0 and 96.3%. The alkaline soil shows relatively higher F sorbing capacity than the acid and neutral soil. For both the acid and neutral soils, increasing P addition has increased F sorption at all F levels. For the alkaline soil, however, this effect was clear only at the low F level. The formation of insoluble F minerals may be enhanced by the addition of P to the soils. But the formation of a mineral such as fluoroapatite is unlikely because precipitation reactions are very slow in soils. MacIntire et al. (1947), Jung (1953), and Scharrer et al. (1953) reported that the precipitation of fluoroapatite following F application to soils requires a long time.

Dry Matter Yield (DMY)

Highly significant effects of soil, F addition and their interactions on DMY of barley plants were observed (Table 1). Similar results were obtained by Prince et al. (1949) for tomato and by Singh et al. (1979a, 1979b) in their study on rice and wheat.

Fluoride addition appeared to have a significant negative effect on DMY for barley grown on the acid and neutral soil (Table 2). The reduction of DMY due to F addition can be attributed to: a) accumulation of toxic amounts of F in soils, b) increasing the mobility of other toxic elements in soils (e.g., Al), and/or c) the effect on nutrient balance in the plant.

For the alkaline soil, F addition had no effect on DMY. This result may reflect the minor effect of F addition on both the pH and the solubility of Al in alkaline soils (Elrashidi and Lindsay, 1987). On the other hand, increasing P addition from 50 to 550 mg kg^{-1} soil at all levels of added F had no clear effect on DMY for plants grown on the three soils (Table 2).

TABLE 3. Effect of fluoride and phosphate addition on F, P, Al, and Mn uptake by barley grown on the three soils.*

F applied mg kg^{-1} soil	Cahaba soil (acid)			Weld soil (neutral)			Haverson soil (alkaline)		
	P applied mg kg^{-1} soil								
	50	150	550	50	150	550	50	150	550
	F uptake mg pot^{-1}								
0	0.048ax	0.063ax	0.050ax	0.025ax	0.028ax	0.025ax	0.110az	0.078ay	0.055ax
100	0.128ax	0.173by	0.130ax	0.190by	0.150axy	0.120ax	0.210ay	0.158bx	0.128bx
400	1.858by	1.060cx	0.578bx	2.555cz	1.345by	1.058bx	0.240ax	0.235cx	0.288cx
1000	-	-	-	-	-	-	0.408bx	0.545dx	0.675dx
	P uptake mg pot^{-1}								
0	6.32bx	10.91bx	28.45by	8.34ax	10.99ax	22.28aby	19.25bx	24.20ay	31.40bz
100	3.03ax	8.29ay	23.58bz	12.05bx	14.15bx	23.30by	19.25bx	24.50axy	26.30ay
400	2.76ax	6.21ay	9.17ay	11.93bx	16.55by	18.93ay	16.48ax	23.05ay	29.40abz
1000	-	-	-	-	-	-	17.78ax	25.05ay	30.90bz
	Al uptake mg pot^{-1}								
0	5.74ax	7.71ay	7.76ay	4.50ax	5.12ax	6.49ay	7.38ax	7.12ax	7.99ax
100	6.52ax	8.11ay	8.08ay	6.68bx	7.03bx	7.42ax	6.68ax	6.55ax	5.70ax
400	40.63by	22.33bx	19.73bx	6.80bx	11.24cy	16.30bz	7.61ax	7.97ax	7.17ax
1000	-	-	-	-	-	-	7.21ax	8.82ax	8.26ax
	Mn uptake mg pot^{-1}								
0	14.88bx	16.73cx	29.85by	3.04ax	3.42ax	6.74ay	10.55az	9.26ay	8.32abx
100	9.69ax	13.08bx	26.55by	4.38bx	5.16bx	7.01ay	10.58ay	9.14axy	7.72ax
400	6.59ax	6.62ax	11.93ay	3.92abx	5.07bxy	6.16ay	10.21ax	8.61ax	8.81bx
1000	-	-	-	-	-	-	10.53ay	9.27ax	8.28abx

*In each soil, means within columns with the same letter (a,b,c, or d) and means within rows with the same letter (x,y, or z) are not significantly different at the 5% level according to Duncan's Multiple Range Test.

A multiple regression equations (Table 4), including soil extractable F and P along with soil pH as independent factors, gave highly significant correlations with DMY for both the acid and neutral soil. No relation was observed for the alkaline soil.

Fluoride Uptake

The results indicate that soil F addition and their interactions together and with P had highly significant effects on F uptake by barley plants (Table 1). The data on F uptake within each soil (Table 3) indicate that F addition had the highest effect on the neutral soil, followed by the acid soil while the least effect on F uptake was observed for the alkaline soil.

The data in Table 3 also indicate generally that addition of P depressed the F uptake by plants growing on these soils. Similar results were obtained by Prince et al. (1949) and Singh et al. (1979a, 1979b). Phosphorus addition may enhance a formation of insoluble F minerals in the soils.

Highly significant correlations of 0.89, 0.95, and 0.86 were obtained between soil extractable F and F uptake by plants for the acid, neutral, and alkaline soil, respectively. Including soil extractable F and P along with pH in a multiple regression equation (Table 4) could predict most of the variations in the values of F uptake by plants.

Phosphorus Uptake

Highly significant effects of soil, the F and P additions and their interactions on P uptake were obtained (Table 1). Analysis of the data within each soil (Table 3) shows that increasing F addition depressed P uptake by plants grown on the acid soil. No clear trend for the effect of F addition on P uptake was observed for the neutral and alkaline soils.

Expectedly in all the soils, addition of P increased significantly P content of plants. For both the acid and neutral soils the magnitude of that increase decreased with increasing F addition. For the alkaline soil, however, The relation between P addition and P uptake was not much affected by F addition.

Highly significant correlations of 0.92, 0.87, and 0.73 were observed between soil- extractable P and P uptake for the acid, neutral, and alkaline soil, respectively. A multiple regression analysis (Table 4) including soil-extractable P and F along with soil pH accounted for 89.5, 78.9, and 60.8% of the variations in the values of P uptake for the acid, neutral, and alkaline soil, respectively.

Aluminum Uptake

Soil F and P additions and their interactions have highly significant effects on Al uptake by barley plants (Table 1). Fluoride addition had significant effects on increasing Al uptake for both the acid and neutral soil (Table 3). For instance, the

TABLE 4. Multiple regression equations relating soil pH, soil extractable F and P to dry matter yield and various elements absorbed by barley grown on the three soils.

Dependent variables†	Intercept	Coefficients			R^2
		Soil F	Soil P	pH	
Cahaba soil (acid)					
Dry matter	1.931	-0.038***	0.011	0.365	0.81***
F-uptake	-1.611	0.018***	0.001	0.342	0.80***
P-uptake	-7.217	-0.065***	1.023***	2.952	0.90***
Al-uptake	-19.490	0.356***	0.153	4.916	0.76***
Mn-uptake	-12.011	-0.114***	0.846***	5.527*	0.88***
Weld soil (neutral)					
Dry matter	7.905	-0.016**	0.001	-0.650	0.37***
F-uptake	-0.639	-0.021***	0.0004	0.105	0.91***
P-uptake	19.240	0.007	0.106***	-1.410	0.79***
Al-uptake	16.098	0.040*	0.022	-1.822	0.59***
Mn-uptake	7.571	-0.001	0.026***	-0.631	0.76***
Haverson soil (alkaline)					
Dry matter	4.863	-0.006	-0.013	0.279	0.091
F-uptake	1.466	0.007***	-0.004	-0.182	0.752***
P-uptake	29.886	-0.090**	0.483***	-1.272	0.608***
Al-uptake	7.725	0.017	-0.043	0.001	0.036
Mn-uptake	3.552	0.017	-0.077**	0.858	0.301***

*, **, ***Indicate significance at 0.05, 0.01, and 0.001 level of probabililty, respectively.

†All variables are expressed as mg pot^{-1} except dry matter, which is expressed as g pot^{-1}.

addition of 400 mg F kg^{-1} soil, at the highest P treatment, increased Al uptake from 7.76 to 19.7 mg pot^{-1} and from 6.49 to 16.3 mg pot^{-1} for the acid and neutral soil, respectively. On the other hand, addition of F to the alkaline soil resulted in only minor increases in Al uptake. Addition of 1,000 mg F kg^{-1} of soil, at 550 mg P kg^{-1} of soil, increased Al uptake from 7.99 to 8.26 mg pot^{-1}.

In earlier study in this laboratory, Elrashidi et al. (1987) concluded that addition of F increased considerably the solubility of Al in acid soils whereas it had only a minor effect on alkaline calcareous soils. Polomski et al. (1982) reported that F addition increased the solubility of Al, Fe, and OM in soils. Elrashidi and Lindsay

(1986a) studied F solution complexes in soils. They found that Al-F complexes contribute significantly to the total soluble F in acid soils. In the current study, a highly significant correlation of 0.96 was obtained between F and Al uptake by barley plants grown on the acid soil.

For both the acid and neutral soils, the extractable F is the most important parameter influencing Al uptake. Highly significant simple correlations of 0.87 and 0.60 were obtained between extractable F and Al uptake for the acid and neutral soil, respectively. No relation was obtained for the alkaline soil.

The effect of P addition, at different levels of F, on Al uptake was investigated for the three soils. Only at the highest F level in the acid soil that P addition decreased significantly Al uptake (Table 3). For both the neutral and alkaline soils, the effect of P addition on Al uptake was not clear. Extractable F and P along with soil pH were able to predict 76.1 and 58.9% of the variations in Al uptake for the acid and neutral soils, respectively.

Manganese Uptake

In general, soil, the F and P additions and their interactions had a highly significant effect on Mn uptake by barley plants (Table 1). Increasing the F addition to the acid soil decreased significantly the uptake of Mn by plants (Table 3). The effect of F addition was not clear for both the neutral and alkaline soils. Singh et al. (1979a) found that increasing F addition decreased the macro-nutrient content of rice plants in alkaline soils.

For both the acid and neutral soils, the data given in Table 3 suggest that increasing P additions increased significantly the Mn content of the plants at all F levels. On the contrary, P additions decreased Mn uptake by plants grown on the alkaline soil. No reasonable explanation could be offered for the decrease in Mn uptake.

Similar responses, as to the data discussed above for Mn, were found for the uptake of other elements (e.g., Fe, Zn, Cu, K, Ca, and Mg) as a result of the F and P additions. No data for these elements are given in this report.

CONCLUSIONS

(1) Most of the soluble F added to soils is converted into insoluble chemical forms which are not available to plants. The addition of P appears to enhance the conversion process, particularly under neutral and acidic environments.
(2) Addition of soluble F to soils of low pH can result in serious damage to vegetation. However, plants growing in alkaline calcareous soils are able to maintain a normal growth even with addition of high amounts of soluble F.
(3) In general, addition of P to soils depresses F uptake by plants. The addition of P may enhance the formation of insoluble F minerals in soils.
(4) The addition of F increases Al uptake particularly for plants grown on acid soils.

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